A New Active Snubber Circuit for PFC Converter

Burak Akın
Yildiz Technical University/Electrical Engineering Department, Istanbul, TURKEY
Email: bakin@yildiz.edu.tr

Abstract—**In this paper, a new active snubber circuit is developed for PFC converter. This active snubber circuit provides zero voltage transition (ZVT) turn on and zero current transition (ZCT) turn off for the main switch without any extra current or voltage stresses. Auxiliary switch turns on and off with zero current switching (ZCS) without voltage stress. Although there is a current stress on the auxiliary switch, it is decreased by diverting it to the output side with coupling inductance. The proposed PFC converter controls output current and voltage in very wide line and load range. This PFC converter has simple structure, low cost and ease of control as well. In this study, a detailed steady state analysis of the new converter is presented, and the theoretical analysis is verified exactly by 100 kHz and 300 W prototype. This prototype has 98% total efficiency and 0.99 power factor with sinusoidal current shape.**

Index Terms— **Power factor correction (PFC), soft switching (SS), ZCS, ZCT, and ZVT.**

I. Introduction

In recent years, the power electronic systems and devices, which are used more frequently, create harmonic currents and pollute the electricity network. Harmonics have a negative effect on the operation of the receiver, who is feeding from the same network. Some sensitive equipments cannot work right. Nowadays, designers provide all the electronic devices to meet the harmonic content requirements.

AC-DC converters have drawbacks of poor power quality in terms of injected current harmonics, which cause voltage distortion and poor power factor at input ac mains and slow varying ripples at dc output load, low efficiency and large size of ac and dc filters [8]. These converters are required to operate with high switching frequencies due to demands for small converter size and high power density. High switching frequency operation, however, results in higher switching losses, increased electromagnetic interference (EMI), and reduced converter efficiency [13]. To overcome these drawbacks, low harmonic and high power factor converters are used with soft switching techniques. High switching frequency with soft switching provides high power density, less volumes and lowered ratings for the components, high reliability and efficiency [1-3], [7], [10], [12], [13], [16].

In principle, the switching power losses consist of the current and voltage overlap loss during the switching period, power diode's reverse recovery loss and discharge energy loss of the main switch parasitic capacitance. Soft switching with Pulse Width Modulation (PWM) control has four main groups as zero voltage switching (ZVS), zero current switching (ZCS), zero voltage transition (ZVT) and zero current switching (ZCT). ZVS and ZCS provides a soft switching, but ZVT and ZCT techniques are advanced, so switching power loss can be completely destroyed or is diverted to entry or exit [10].

In this study, to eliminate drawbacks of the PFC converters, the new active snubber circuit is proposed. The proposed circuit provides perfectly ZVT turn on and ZCT turn off together for the main switch, and ZCS turn on and turn off for the auxiliary switch without an important increase in the cost and complexity of the converter. There are no additional current or voltage stresses on the main switch. A part of the current of the auxiliary switch is diverted to the output with the coupling inductance, so better soft switching condition is provided for the auxiliary switch. Serially added D_2 diode to the auxiliary switch path prevents extra current stress for the main switch. The aim of this proposed converter is to achieve high efficiency and high switching frequency PFC converter with sinusoidal current shape and unity power factor at universal input. The steady state operation of the new converter is analyzed in detail, and this theoretical analysis is verified exactly by a prototype of a 300 W and 100 kHz boost converter.

II. Operation Principles and Analysis

Definitions and Assumptions

The circuit scheme of the new PFC converter is given in Fig. 1. In this circuit, V_i is input voltage source, V_o is output voltage, L_F is the main inductor, C_o is output capacitor, R is output load, S_1 is the main switch, S_2 is the auxiliary switch and D_F is the main diode. The main switch consists of a main switch S_1 and its body diode D_{S1}. L_{R1} and L_{R2} are upper and lower snubber inductances, C_R is snubber capacitor, and D_1, D_2, D_3 and D_4 are the auxiliary diodes. L_m is the magnetization inductance; L_{il} and L_{ol} are the input and output leakage inductances of the transformer

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respectively. Air gap and leakage inductance ratings are assumed sufficiently big enough. C_S is the equivalent parasitic capacitor of the main switch, so it is not an additional component to this converter.

For one switching cycle, the following assumptions are made in order to simplify the steady state analysis of the circuit shown in Fig. 1.

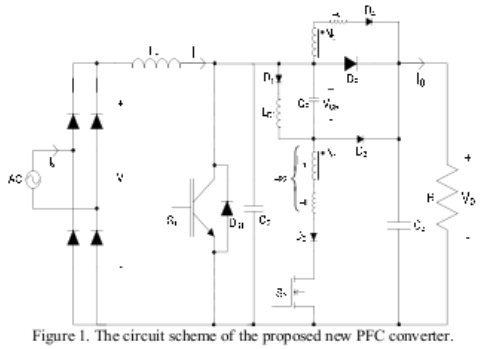

Figure 1. The circuit scheme of the proposed new PFC converter.

put voltage V_o and input current I_i are constant for one switching cycle, and all semiconductor devices and resonant circuits are ideal. Furthermore, the reverse recovery times of all diodes are not taken into account.

Operation Stages

Twelve stages occur over one switching cycle in the steady state operation of the proposed converter. The equivalent circuit schemes of the operation stages are given in Fig. 2 (a)-(l) respectively. The key waveforms concerning the operation modes are shown in Fig. 3. The detailed analysis of every mode of this converter is presented below.

Stage 1 [$t_0<t<t_1$: Fig.2(a)]

First of all, S_1 and S_2 switches are in the off state. I_i input current passes through the D_F main diode at this stage. At $t=t_0$, $i_{S1}=0$, $i_{S2}=0$, $i_{DF}=I_i$, $i_{LR1}=0$, $i_{LR2}=0$ and $v_{CR}=0$ are valid. When the gate signal is applied to the S_2, a resonance starts between L_{R1}, L_{R2} and C_R. Then, S_2 current rises meanwhile D_F current falls. L_{R2} snubber inductance provides turn on switching with ZCS of S_2, D_1 and D_2.

In this interval, depending on transformator conversion ratio, input and output currents of transformator rise and D_F current falls. At $t=t_1$, the sum of the input and output currents of transformator reaches to I_i input current and then, D_F current falls to zero and D_F turns off with ZCS.

Stage 2 [$t_1<t<t_2$: Fig.2(b)]

The main switch S_1 and the main diode D_F are in off state and S_2 is in on state. At $t=t_1$ a resonance starts between C_S-L_{R1}-L_{R2}-C_R. The main switch's parasitic capacitor C_S discharges, at the same time the energy in L_{R2} is transferred to the output side by the coupling inductance. At $t=t_2$, V_{CS} voltage becomes zero and D_{S1} turns on with ZVS, meanwhile D_4 turns off and this interval ends.

Stage 3 [$t_2<t<t_4$: Fig.2(c)]

D_{S1} is turned on at t_2. The resonant between L_{R1}-L_{R2}-C_R continues. After this stage L_{R2} inductance value is equal to the sum of L_{il} and L_m.

In this stage, D_{S1} diode conducts the excess of L_{R2} current from the input current. The interval of this stage is time for the main switch S_1 to turn on with zero voltage transation (ZVT). During this zero voltage transition time, gate signal must be applied to the main switch S_1. So S_1 can be turned on with both ZVS and ZCS by ZVT. At $t=t_3$, L_{R2} current drops to the input current, so D_{S1} turns off with ZCS and S_1 turns on with ZVT. The main switch current starts to rise. At $t=t_4$ S_1 current reaches to the input current level and L_{R2} current becomes zero. When the auxiliary switch current becomes zero, it is time to cut off the gate signal of S_2. So, the auxiliary switch S_2 perfectly turns off with ZCS.

Stage 4 [$t_2<t<t_4$: Fig.2(d)]

This interval starts at $t=t_4$ when S_2 switch is turned off. While S_1 conducts input current I_i, a resonance occurs through L_{R1}-C_R-D_1. The energy in L_{R1} is transferred to the C_R with this resonant. At $t=t_5$, this stage ends when L_{R1} current is equal to zero and C_R voltage reaches its maximum level.

Stage 5 [$t_5<t<t_6$: Fig.2(e)]

During this period, the main switch S_1 conducts input current I_i and the snubber circuit is not active. The duration of this interval is a large part of the on state duration of the standart PWM boost converter and is determined by the PWM control to provide PFC.

Stage 6 [$t_6<t<t_8$: Fig.2(f)]

At $t=t_6$, when the control signal of the auxiliary switch S_2 is applied, a new resonance starts between snubber inductance L_{R2} and snubber capacitor C_R through C_R-L_{R2}-S_2-S_1.

The auxiliary switch S_2 turned on with ZCS through L_{R2}. The auxiliary switch current rises and the main switch current falls due to the resonance. At $t=t_7$, when the S_2 current reaches input current level, the main switch current becomes zero. After S_1 current falls to zero D_{S1} is turned on with ZCS. There is zero current and zero voltage on the main switch S_1. So it is time to cut off the gate signal of S_1 to provide ZCT. A new resonance occurs through the way of C_R-L_{R2}-S_2-D_{S1}. D_{S1} conducts the excess of i_{LR2} from the input current. At $t=t_8$, v_{CR} falls to zero and i_{LR2} current reaches its maximum levels and this interval ends.

Stage 7 [$t_8<t<t_9$: Fig.2(g)]

At t=t8, while v_{CR} voltage starts to be positive, D_1 diode is turned on. A resonance starts between L_{R2}, L_{R1}

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and C_R. L_{R2} current falls again to I_i and D_{S1} current becomes zero. At $t=t_9$, the diode D_{S1} turns off with ZCS. The duration of the on time of the D_{S1} is equal to the ZCT time.

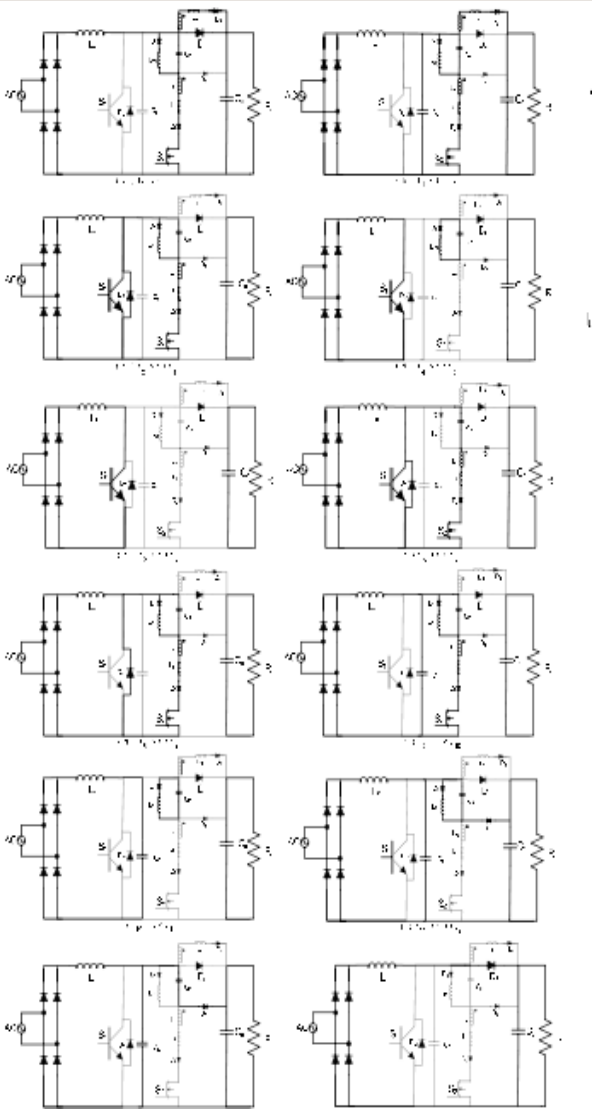

Figure 2. Equivalent circuit schemes of the operation modes

Stage 8 [$t_9<t<t_{10}$: Fig.2(h)]

At $t=t_9$, because i_{LR2} current falls to I_i, a resonance occurs between C_S-L_{R1}-L_{R2}-C_R with this current. i_{LR2} current falls, and at $t=t_{10}$, when i_{LR2} current is equal to zero, S_2 can be turned off. So the auxiliary switch S_2 is turned off perfectly under ZCS.

Stage 9 [$t_{10}<t<t_{11}$: Fig.2(i)]

There are two different closed circuits for this interval. For the first closed circuit, C_S capacitor is charged linearly with I_i and for the second closed circuit, a resonance occurs through L_{R1}-C_R-D_1. At $t=t_{11}$ the sum of v_{CS} and v_{CR} voltages is equal to V_o, so D_3 diode can be turned on.

Stage 10 [$t_{11}<t<t_{12}$: Fig.2(j)]

A new resonance occurs through L_{R1}, C_S and C_R with I_i input current. At $t=t_{12}$, i_{LR1} current falls to zero, so this interval ends. The energy stored in L_{R1} inductance is transferred to the capacitors and load completely.

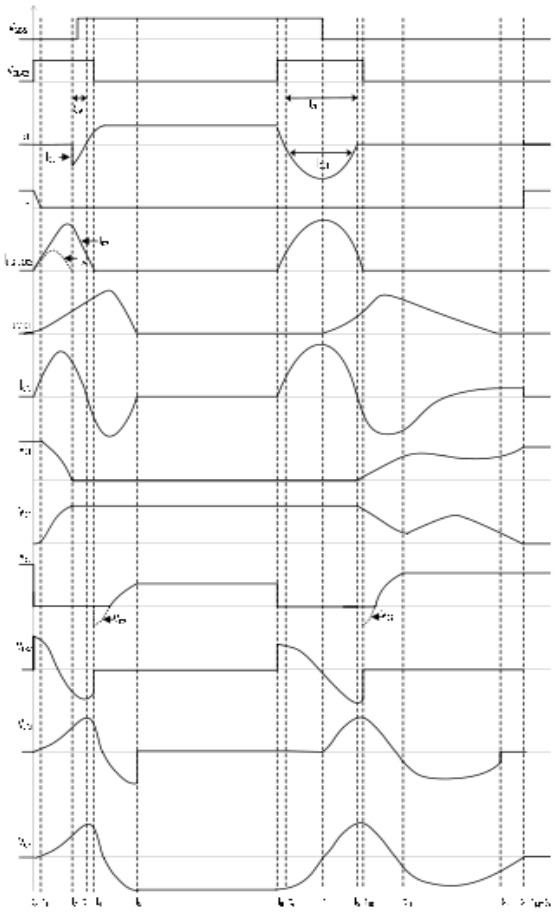

Figure 3. Key waveforms of the operation stages

Stage 11 [$t_{12}<t<t_{13}$: Fig.2(k)]

C_S is charged linearly with constant I_i current and C_R is discharged. At $t=t_{13}$, when C_S capacitor voltage reaches to V_o, C_R capacitor voltage falls to zero and D_F diode is turned on with ZVS.

Stage 12 [$t_{13}<t<t_{14}$: Fig.2(l)]

During this stage, the main diode D_F conducts input current I_i and the snubber circuit is not active. This time period is determined by the PWM control and large part of the off state of the converter. Finally, at $t=t_{14}=t_0$, one switching period is completed and then next switching period starts.

EXPERIMENTAL RESULTS

A prototype of a 300 W and 100 kHz PFC converter is shown in Fig. 4 to verify the predicted analysis of the

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proposed converter. The PFC converter is obtained by adding ZVT-ZCT-PWM active snubber circuit to the boost converter, which is fed by universal input AC line. The boost converter consists of the main inductance L_F, the main switch S_1 with the antiparallel diode D_{S1} and the main diode D_F. The active snubber circuit consists of the auxiliary switch S_2, four auxiliary diodes D_1, D_2, D_3,and D_4, the snubber inductances L_{R1} and L_{R2} with the coupling inductance and the snubber capacitor C_R. For output receiver, resistive load is aplied to the output of the converter.

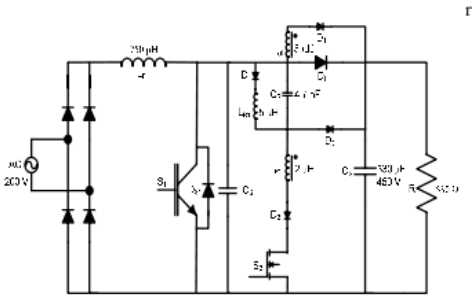


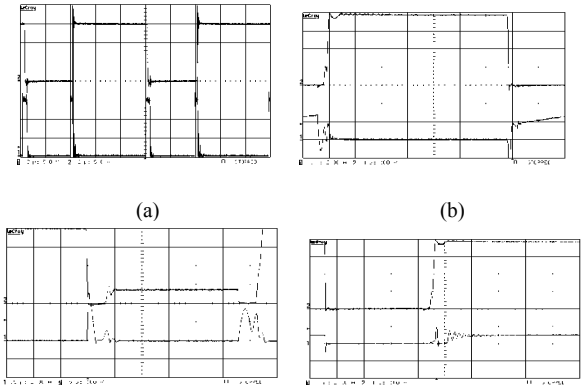
Figure 4. The prototype circuit scheme of the PFC converter.

The value of 200 V AC is applied to the input of the converter. Then, AC volatage is rectified to DC voltage for the boost converter. For the PFC converter, input bulk filter capacitor is not used after rectifier. This is because to control the line current to follow sinuzoidal current for PFC. The L_F main inductance is calculated to process continues current mode (CCM) for the input line. The L_{R1} snubber inductance of the snubber circuit was chosen as 5 µH, the L_{R2} snubber inductance as 2 µH, L_{ol} the coupling inductance as 3 µH and the C_R snubber capacitor as 4.7 nF. Input inductance L_F was choosen as 750 µH to shape input current as sinusoidal and output capacitor C_o as 330 µF to have constant output voltage.

In the Fig. 5 (a), the control signals of the main and the auxiliary switchs are shown. The auxiliary switch operates twice in one switching cycle of the main switch and the main switch operates at 100 kHz. In Fig. 5 (b), it can be seen that S_1 is operated under soft switching, for both turn on and turn off processes. Also, there are no overlap between voltage and current waveforms for the main switch S_1. During the turn on and turn off processes of the main switch S_1, its body diode is turned on. Therefore, ZVT turn on and ZCT turn off processes are perfectly realized for the main switch S_1. Furthermore, from the voltage waveform, there is no any additional voltage stress on the main switch. In the current waveform, there is a rising current to provide CCM for PFC converter.

In Fig. 5(c) the voltage and current waveforms of the auxiliary switch are shown. The auxiliary switch is operated in both ZVT and ZCT processes of the main switch S_1 so, the auxiliary switch is operated at 200 kHz. Both ZVT and ZCT operations of the main switch, the conduction time of the auxiliary switch is very short. The auxiliary switch is turned on and off under ZCS. Because the loss of the resonance circuit, the peak current of S_2 in the ZCT interval is lower than the ZVT interval. And also the coupling inductance transfers the resonance energy to the output load for better efficieny. However, there are no additional voltage stresses on the semiconductors while the active snubber circuit operates under soft switching.

The main diode is turned on under ZVS and turned off under ZCS and ZVS. It can be seen in Fig. 5(d), there are no additional voltage and current stresses on the main diode. For the main and the auxiliary diodes, Silicone Carbide (SIC) diodes are used. SIC diodes have greater reverse recovery time with 10 ns.

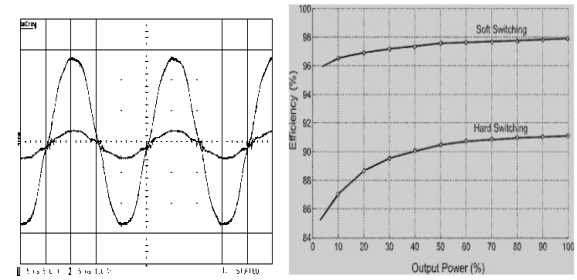


(a) (b)

(c) (d)

Figure 5. Some oscillograms of the PFC converter. a) Control signals of S_1 and S_2. b) Voltage and current of S_1. c) Voltage and current of S_2. d)Voltage and current of D_F .

Input AC current and voltage waveforms can be seen in Fig. 6(a). The power factor of the proposed PFC converter is near unity with 0.99 value. Moreover, it is observed that the proposed PFC converter operates in CCM and keeps operating under soft switching conditions successfully for the whole line and load ranges. From Fig. 6(b), it is seen that the overall efficiency of the proposed PFC converter reaches a value of 98% at full output load.



(a) (b)

Figure 6. a) Voltage and current of input AC line b) Overall efficiency of the proposed converter

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Because the converter power loss is dependent on circulating energy, it becomes lower as the load current falls in the proposed PFC converter.

CONCLUSIONS

In this study, advanced and modern active snubber circuit is used for the new PFC converter. For this purpose, only one auxiliary switch and one resonant circuit is used. ZVT and ZCT techniques provide soft switching for the main switch and also for the other semiconductors. This new active snubber circuit is applied to the boost converter which is fed by rectified universal input AC line. As a result, the new PFC converter was carried out. This new PFC converter is realized with 200 V AC input mains, to provide 400 V DC output. The new PFC converter works with 100 kHz for 300 W output load. Oscilloscope and other measurement results are carried out briefly in this paper.

The main switch turns on with ZVT and turns off with ZCT, the auxiliary switch turns on and turns off with ZCS. Also, other semiconductors process with soft switching even at light load conditions. By the coupling inductance, current stress on the auxiliary switch is transferred to the output load to improve efficiency of the converter. The serially added diode to the auxiliary switch path prevents the incoming current stresses from the resonant circuit to the main switch. There are absolutely no current or voltage stresses on the main switch. Although there is no voltage stress on the auxiliary switch, the current stress is reduced by transferring this energy to the output load by the coupling inductance. Finally, at full load 98% efficiency is achieved.As a result, this new PFC converter has many desired features of the ZVT and ZCT converters and also it solves many drawbacks of the PFC converters. It was observed that the operation principles and the theoretical analysis of the new PFC converter were exactly verified by a 300 W and 100 kHz prototype. Additionally, at full output load, the new PFC converter reaches % 98 total efficieny and 0.99 power factor with sinuzoidal current shape.

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